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ELECTRICAL REVIEW

June • 1940

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ELECTRICAL REVIEW

C O N T E N T S

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BEATING BLACK-OUTS

W. G. Kelley, Plant Design Engineer

COMMONWEALTH EDISON COMPANY • CHICAGO, ILLINOIS

Non-belligerents have their "black-outs" too . . . interruptions of power supply that are costly to customer and utility alike. Over a luncheon table were evolved stud bushings . . . a cure for over 75% of the biggest source of transformer failures.

Ten years have passed since the first stud bushing distribution transformer was put into service. This period viewed in restrospect shows that this development represented an advance in the art of transformer design and construction. It also indicates how much can be accomplished by the joint effort of operating companies and manufacturing companies in reducing maintenance costs for the utilities.

The stud bushing distribution transformer had its inception over a luncheon table in Chicago. At this meeting there was an informal discussion of a study that had been made to determine the costs that result from transformer outages. This report showed that approximately seventy percent of the expense involved in transformer failure could be attributed directly or indirectly to leads. Naturally the question arose: "Why not eliminate the leads?"

Furthermore, a large part of the expense due to transformer outages was traceable to the cost of taking the transformer down off the pole, transporting it to the repair shop, and retransporting and reinstalling it later.

From these two outstanding points deduced from the report came the decision to produce a detachable bushing — one that any lineman could replace in the field without the necessity of taking the transformer to the repair shop. Hence, the first designs worked out were called detachable-bushing transformers. The primary idea was to make replacement easy. To this end the bushings were held in place in the transformer tanks by means of keeper plates and set screws instead of cementing them in place with compound.

Cooperative development

After this first meeting when design engineers from various manufacturing companies were called in, it was suggested that a distribution transformer be made with bushing construction similar to that approved in power transformer practice. The first sketches showed a cover type of bushing. Serious objections to this came from the utility company's operating department because joint pole occupancy necessitated limiting the head room. It seemed better judgment to lay out a design that would not involve any changes in utility companies' standards and a design that would fit into present locations without system changes. These considerations dictated the final decision to put the bushings in the side of the tank. The transformer designers' problems then became one of inside clearance.

Until that time not many persons had realized how much dependence the transformer designer had been placing on the insulation of the leads. Porcelain bushings on the 2400 volt lead type units had in many cases been quite small. Some of the earlier ones looked almost like porcelains out of a knob and tube wiring job. This construction was satisfactory as long as the transformer was new and the lead insulation had not weathered. However, after the leads had been used a few times as improvised handles to pull the transformers around, and after the weather had attacked the lead insulation for a year or two, the original flashover or puncture values were materially decreased.

In the changeover from a piece of porcelain that was adequate when used with insulated wire to one adequate for use with a bare stud, the bulk of the bushing grew surprisingly; but, by using circular tanks with no constriction at the top, adequate clearances were secured. This design is shown with the cover removed in Fig. 1.

The best teacher

At this stage of the development, the design was considered ready to be subjected to field experience. A few transformers were purchased and installed. Ex-

AT LEFT: Projection welding the bottom plate of a distribution transformer. The recessed construction gives added protection against rust and mechanical damage from handling.

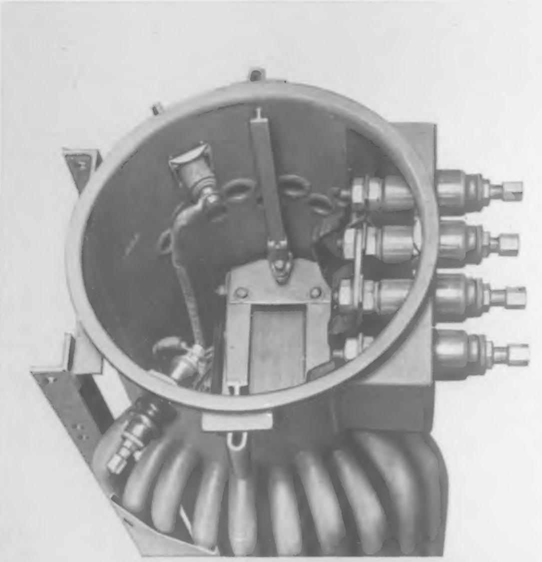


Fig. 1

Fig. 2

perience was prompt in arriving. The first lightning storms that played along the lines where these new transformers were operating blew the covers off several units. Investigation showed that the detachable bushings had flashed over on the inside of the tanks, ignited the oil vapor in the air space, and removed the covers. However, none of the windings failed, nor were any of the bushings damaged by this trial. The bushings were wiped off, the covers replaced, and the units returned to service without being removed from the poles.

This experience again brought to the foreground one of the earlier lessons in coordinating insulation, as it was apparent that the bushings should be designed to flash over outside the tank before the windings failed and also before flashover could occur on the inside ends of the bushings. Adherence to this fundamental principle of design, discovered early in the development period, plus the use of paper-insulated conductors on both the primary and secondary windings, has made the present stud bushing transformer outstanding in its performance.

No other important design changes were necessary after coordination of insulation was worked out. Details have been altered from time to time to meet the operating company's system needs and to permit economies in manufacture. Secondary bushings, which were originally separate for each lead as in Fig. 2, had been made gang type on units up to 50 kva as in Fig. 3. The original "U" bolt type connector remains unchanged in all but the small sizes. Paper-insulated, cotton-covered windings are still used on both the primary and secondary.

This lack of change is the more remarkable when it is recalled that a large number of operating and manufacturing engineers were directly interested in this development. Such a venture always brings forth a wealth of ideas, many of which may be good. There is always a temptation to include these as improvements in any development. However, after a satisfactory design had been achieved, it was decided that additional changes would be made with caution, and gadgets would be added only if and when excellent reason for their use could be shown. This status holds today.

Results

These stud bushing transformers are still being installed as independent units. All protective equipment is mounted separately and not attached to the transformer. This policy best permits the operating company to take advantage of improvements in any item of material entering into the distribution system and reduces the cost for maintenance of any individual unit of the assembly.

In August, 1928, the first stud bushing transformer was installed in Chicago. At that time the operating company had approximately 28,000 overhead distribution transformers on their system. Records of transformer winding failures for the three years, 1926, 1927, and 1928, showed failures due to lightning alone as follows:

1926 — 0.30%
1927 — 0.30%
1928 — 0.41%

These records show the conditions as they existed before the transformers without leads were developed and also before lightning arrester interconnection had been attempted. Outages have been materially reduced by interconnection, but the new transformer design has also been responsible for a further reduction in outages. A table showing the total stud bushing transformers of all makes installed by years and the total failures among these units from all causes is given below:

Approximate Number of Stud Type Bushing Transformers on Overhead System		Number of Winding Failures Caused by		
		Lightning	Grounds	Unknown
Dec. 31, 1928	338	..	...	..
Dec. 31, 1929	3442	..	..	2
Dec. 31, 1930	4679	1	..	..
Dec. 31, 1931	5682	1	..	1
Dec. 31, 1932	5911	3	..	..
Dec. 31, 1933	6071	5	..	1
Dec. 31, 1934	6515	3	..	..
Dec. 31, 1935	6993	..	2*	1
Dec. 31, 1936	7797	2	..	1
Dec. 31, 1937	8770	7	..	1
Dec. 31, 1938	9591	2	..	..

* These two were in an open-delta connected bank, and the failures were due to a heavy ground on the customer's equipment.

Up to December 1, 1939, the company had installed approximately 33,000 overhead distribution transformers, and the winding failures due to lightning alone for the three years 1936, 1937, and 1938 are as follows:

Winding Failures Due to Lightning Only		
	Lead Type Transformers	Stud Type Transformers
1936	0.21%	0.026%
1937	0.21%	0.080%
1938	0.15%	0.021%

How much of this improvement can be accredited to the stud bushing transformer can best be judged from a study of the above table.

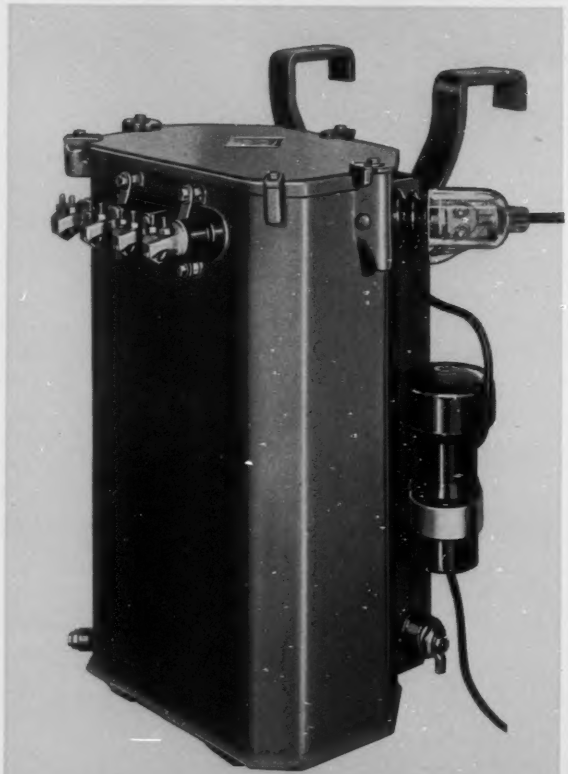
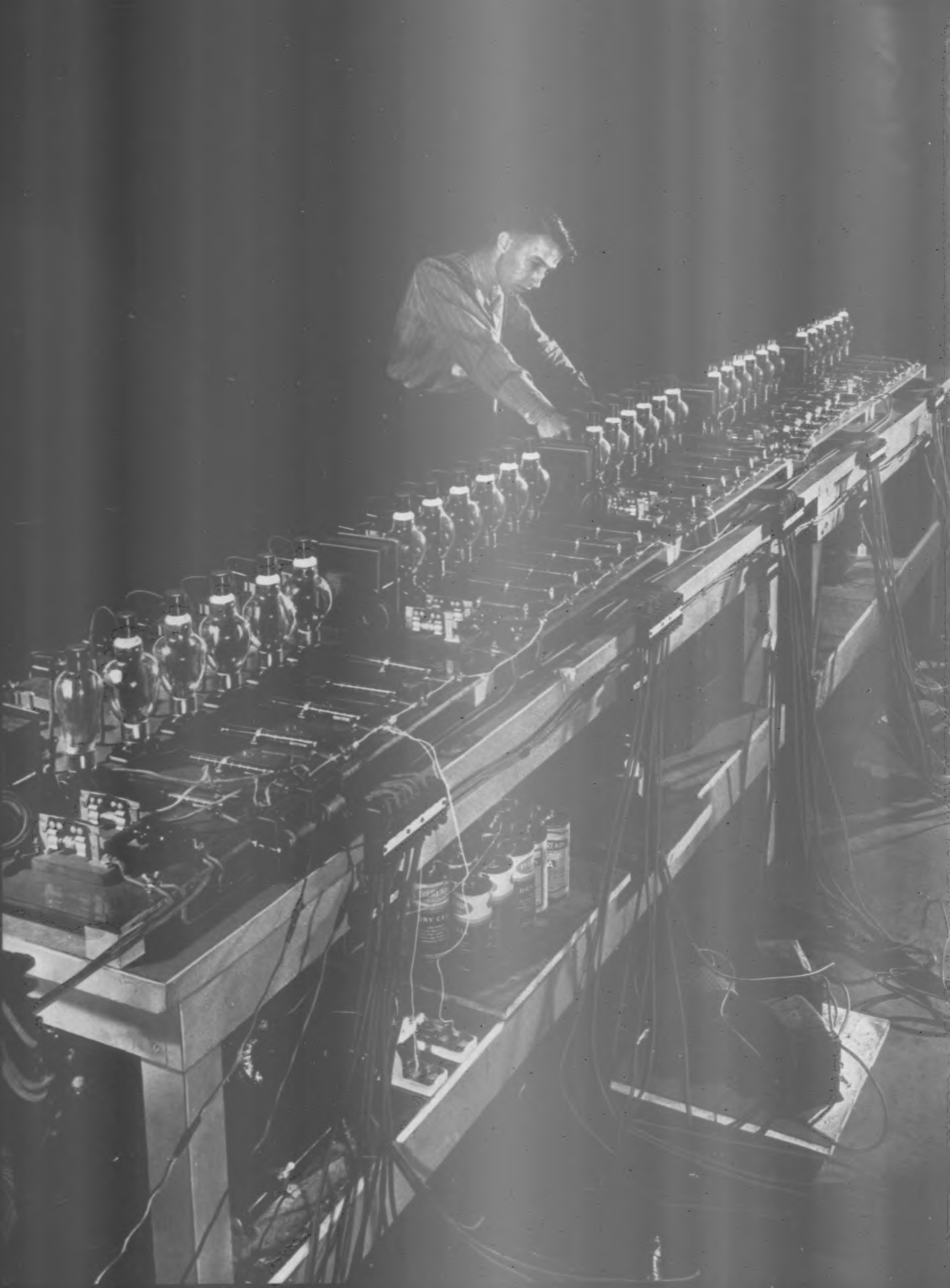


Fig. 3

AT RIGHT: A batch of core and coil assemblies for small distribution transformers are impregnated after baking.



THE EXCITRON

S. R. Durand

RECTIFIER DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

One of the first steps in increasing efficiency of any apparatus is to combine several separate units into one machine. But the latest development in mercury arc rectifiers reverses this principle . . . and, by doing so, gives you a higher efficiency.

A recent advance in the field of electronic power equipment has been the development of a single-anode mercury pool type rectifier equipped with auxiliary electrodes for establishing and controlling the arc current. A group of individual tanks assembled together to constitute a polyphase rectifier has been named an "Excitron" unit.

The basic principle of operation of an Excitron rectifier is the same as the well-known multi-anode steel tank units, since rectification of alternating current into d-c power is accomplished by the uni-directional flow of arc current. The main difference between the two types of rectifiers is that each anode of an Excitron unit is not exposed to the highly ionized mercury vapor of the main arc current during its non-firing inverse voltage period as in a multi-anode tank and, therefore, can be located closer to the mercury pool of its individual tank. This results in a much lower arc drop loss and a resultant improvement in the efficiency of operation.

In order to enable the main arc current to flow in any type of mercury pool rectifier, it is essential to establish first a cathode spot on the surface of the pool. This is accomplished in each tank of an Excitron rectifier by a mercury jet ignition device and an automatic excitation control circuit. The ionization of the mercury vapor produced by the continuously maintained excitation arc is so slight in comparison to that produced by the main arc current that special shielding of the main anode is not necessary in single-anode rectifiers even though the anode is located only a few inches away from the mercury pool.

Individual tanks

A picture of a six-tank Excitron rectifier is shown in Fig. 1 and a cross-section diagram of an individual tank in Fig. 2. Each tank includes a mercury pool cathode at the base and a graphite anode mounted directly above it. The anode is supported by a shaft projecting through an insulator which is sealed into the top plate. A graphite control grid is located just below the anode, and two shielded excitation anodes are mounted between the grid and the mercury pool. The mercury jet ignition device is incorporated in the cathode plate.

In order that the cathode spot will never travel up the side of the housing, the cathode plate is insulated from the housing by means of a seal protected behind a quartz ring. Since quartz is a very poor conductor of heat and because the seal is made between flanges on the cathode plate and housing in close contact to the cooling coil, this insulating seal is thoroughly protected from the possibility of damage due to excessive temperature.

Each tank of an Excitron rectifier unit is cooled by the flow of water through a copper cooling coil or steel jacket attached to the outside walls. Further cooling is effected by the radiation of heat conducted up through the anode shaft to a fin-type aluminum radiator. Copper cooling coils are furnished to minimize the problem of corrosion when direct cooling from a fresh water supply is used. Steel water jackets can be furnished when indirect cooling through a heat exchange unit is necessary or desirable because of the presence of too high a content of insoluble matter or corrosive chemicals in the fresh water supply.

The steel anode shaft supporting the graphite anode head is hollow so that a copper conducting bar can be fitted into it. The copper bar is thus protected from the amalgamating action of hot mercury vapor in the tank while serving as an efficient conductor of heat to the radiator surfaces. The electrical connection to the anode is made at the end of the copper bar above the fin-type radiator.

AT LEFT: Typical set-up for the electronic engineering research that preceded the development of the Excitron.

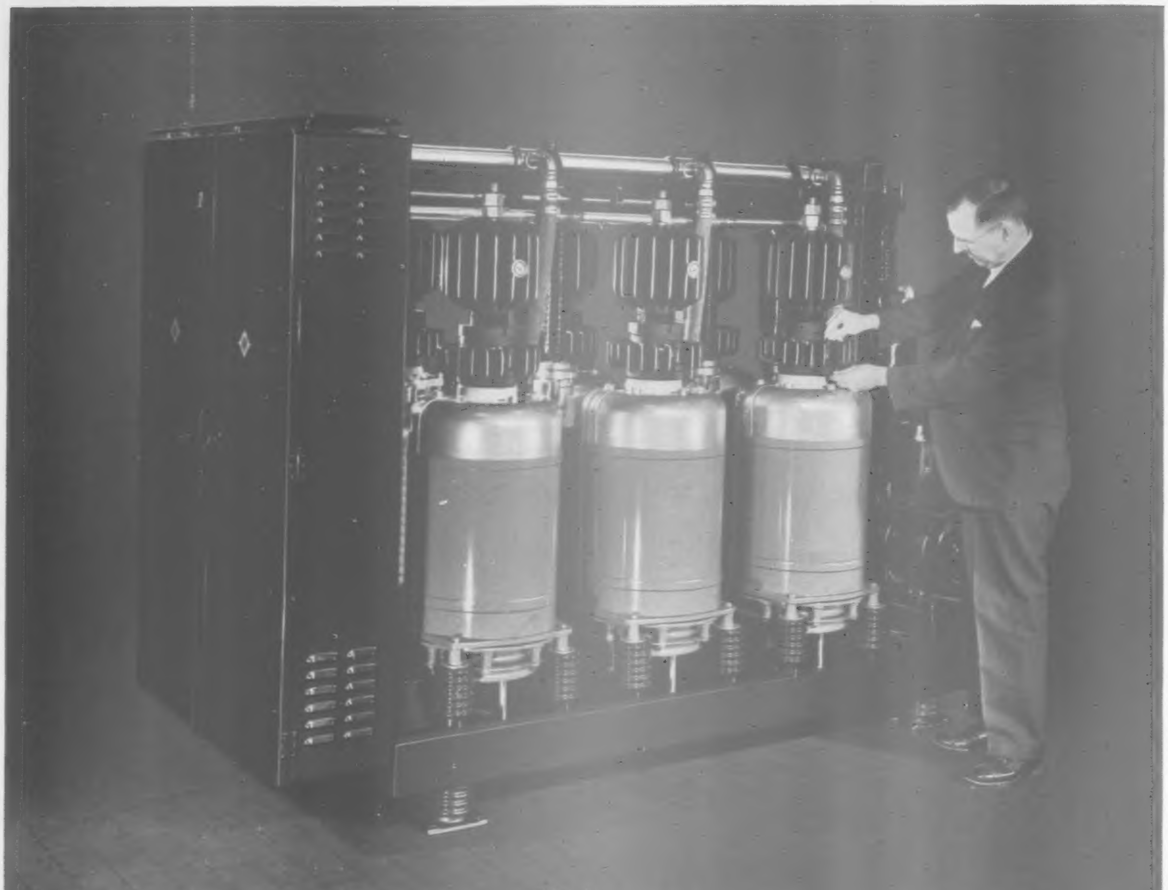


Fig. 1

Grouping

Single-anode rectifier tanks are usually assembled in a group of six to form a six-phase Excitron rectifier. For double six-phase or for twelve-phase rectification, two sets of six tanks each are provided.

A typical arrangement of an Excitron rectifier is shown in Fig. 3. The tanks are mounted on a channel-iron frame in two rows with three tanks in each row. A standard high vacuum and rotary vacuum pump are assembled at one end of the frame, and the automatic ignition-excitation control equipment is contained in a cabinet at the opposite end.

Through a small vacuum valve and pipe line each tank is connected to a vacuum manifold supported between the two rows of tanks. The vacuum manifold is equipped with a main vacuum valve and a hot-wire type vacuum gauge. The excitation transformers, excitation relays, and grid transformer are mounted and wired in the control cabinet. Electrical connections to the ignition, excitation and grid terminals of each tank are made through conduits set into the frame.

The cooling circuits of the tanks are connected in parallel, and each cathode coil or jacket is joined through a union fitting to a water inlet pipe mounted in the channel-iron base. The outlet water connection from the top of each tank is made through a short hose to a common discharge pipe supported above the vacuum manifold. All water piping is of copper with streamlined copper fittings.

Ignition-excitation

In Fig. 4 is shown a cross-section diagram of the mercury jet ignition device consisting of a steel tube welded into the bottom of the cathode plate. A plunger is normally held by a spring against a stop ring at the top of the tube. Mercury flows through the center hole in the plunger and fills the entire space beneath it. Upon momentarily energizing the external ignition coil, a strong magnetic field is formed which causes the plunger to be attracted downward. Movement of the plunger results in a solid stream of mercury being thrown up to an ignition anode located above the mercury pool.

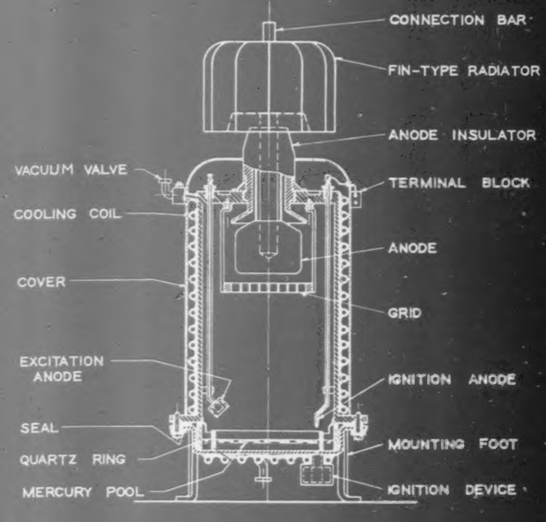


Fig. 2

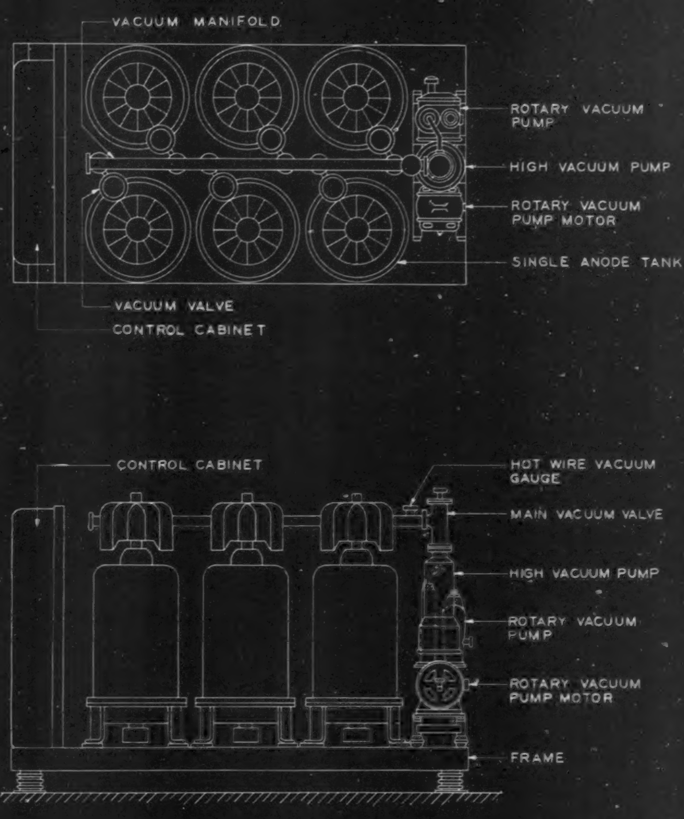


Fig. 3

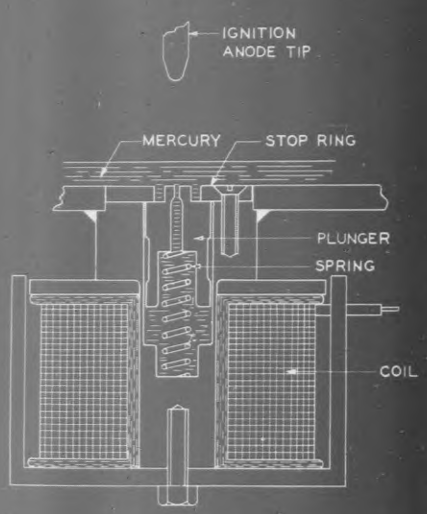


Fig. 4

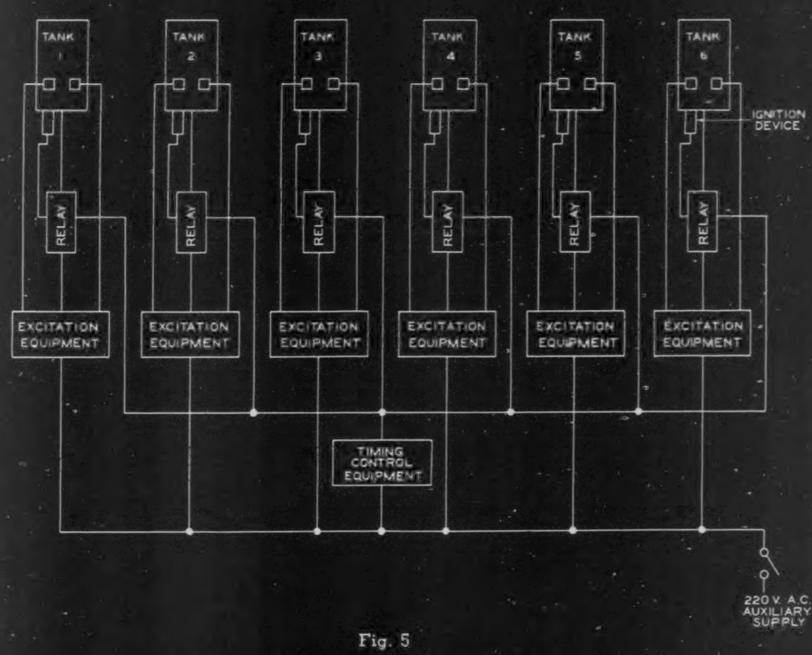


Fig. 5

The time in which the ignition coil is energized is automatically controlled so that the plunger makes a stroke only long enough to enable the mercury stream to make contact against the ignition anode. A potential of a few volts is impressed upon this anode so that, when the stream collapses, an arc is established. This arc is instantly transferred from the ignition anode to the excitation anodes which continuously maintain a cathode spot on the mercury pool.

Each time an Excitron unit is placed in service, excitation must be established in all tanks before the breakers are closed. The operation of the ignition-excitation equipment is controlled by a single switch and is entirely automatic. Excitation is established almost instantly in each tank when the control switch is closed; but, if any tank fails to ignite on the first action of its ignition device, the ignition process is automatically repeated in this tank until excitation is attained.

A line diagram of the excitation circuit is shown in Fig. 5. The excitation equipment associated with each tank includes a small transformer, a reactor, and current-adjusting resistors. The control relay in the excitation circuit of each tank functions to disconnect automatically the timing control equipment from the ignition device when excitation is established. One set of timing relays controls the ignition equipment of all the tanks of an Excitron unit.

The timing and ignition control equipment remains idle while the rectifier is in service. If excitation should ever fail in a tank during operation, the timing equipment is instantly restarted and excitation reestablished without the necessity of tripping the main breaker. However, if for any reason excitation cannot be reestablished in this tank within a period of a few seconds, the Excitron unit is automatically taken out of service.

The load current of an Excitron unit may be regulated by grid control in the same manner as in multi-anode tanks. The current can be adjusted by regulating the value of the grid bias voltage impressed upon the neutral point of the six-phase grid transformer. When an Excitron is operated in parallel with other converting units, the bias can be obtained from a potentiometer connected across the main d-c bus. Otherwise, a small disc type rectifier having a rating of about 200 volts and 200 watts can be most conveniently employed for bias supply.

The total power required for excitation of a six-tank Excitron unit is about equivalent to that required for a large multi-anode tank. Because of the special design and location of the excitation anodes, excitation can be maintained in each tank at very low voltage and current values. Excitation power is generally obtained from a 220 volt, three-phase supply circuit, from which auxiliary source the vacuum pumps, ignition coils, and grid transformer are also operated.

Cooling

An Excitron rectifier can be cooled by regulating the flow of water directly from a supply system through the cooling circuits. The Excitron is not sensitive to operation within a wide range of temperature, and it does not require heaters when idle or when operated at light loads under low ambient temperature conditions. An excessively high temperature, however, results in obtaining a greater mercury vapor pressure than desirable, with the consequent danger of reaching pressures at which backfires are likely to occur.

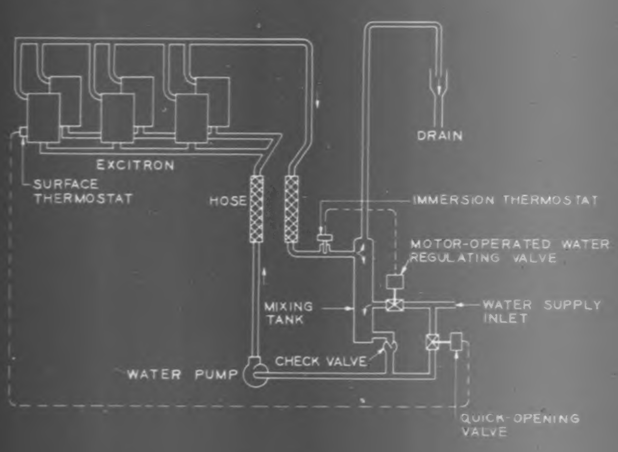


Fig. 6

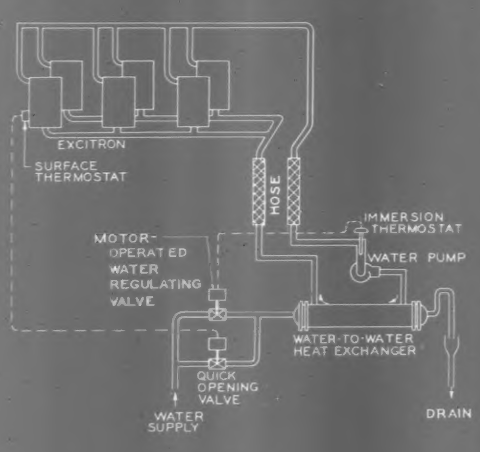


Fig. 7

Therefore, it is advisable to control automatically the flow of cooling water to maintain the temperature at all times within a safe maximum value.

A simple arrangement for automatically controlling the temperature of the single-anode units and also for conserving the amount of cooling water used is to provide a recirculating water circuit to which a regulated amount of fresh water is added under automatic control. A diagram of such a system is shown in Fig. 6.

Water is circulated at a constant rate by a small motor-operated pump. To control the amount of colder fresh water added to the recirculating system a modulating type immersion thermostat in the outlet pipe line responds to temperature changes in the water to regulate the position of a motor-operated water valve. The setting of the immersion thermostat is dependent upon the maximum load to be carried by the Excitron unit; in general, the temperature should be set proportionately lower for units operating continuously at high load currents than for units operating at fluctuating load currents averaging somewhat below the maximum rated value of the equipment.

As added protection for the cooling system if dangerously high temperatures should be attained, surface thermostats are also installed on one or two of the individual tanks to cause the immediate operation of a quick-opening by-pass valve in the fresh water supply to the pump. The setting of the surface thermostats is adjusted several degrees above that of the immersion thermostat so that they will function only under abnormal operating conditions (such as an excessively high overload) which might suddenly occur.

When installations are made in locations where the fresh water supply is not suitable for direct cooling of an Excitron rectifier, a water-to-water or water-to-air heat exchange unit can be used. A diagram of an Excitron rectifier with a heat exchange unit is shown in Fig. 7.

A water-to-water heat exchange unit consists of a bundle of straight tubes assembled in a cylindrical shell. The raw water flows through the tubes, and the pure or treated water is circulated by a pump through the closed circuit of the cylindrical shell and the rectifier unit. The amount of raw water required for cooling is regulated by a motor-operated valve under control of a thermostat immersed in the recirculated water circuit. The advantage of a heat exchange unit is that it can be readily disassembled for cleaning or replacement of the tubes whenever corrosion or deposits make servicing necessary.

A water-to-air heat exchange unit consists of a radiator equipped with a fan. This type of heat exchanger is used when the supply of fresh water for cooling is limited or the cost of obtaining it is excessive.

Degassing

Because of the relatively small volume of each single-anode tank, an Excitron rectifier can be pumped down to a high degree of vacuum within a few minutes. Degassing can be accomplished in all six tanks at the same time by operating them at low voltage, or degassing can be accomplished in one or two tanks at a time by connecting them through resistors to a source of d-c power.

Degassing or "forming" can generally be carried out in a shorter time on these small tanks than in larger multi-anode units because the gases emitted from the internal graphite parts are drawn off much more quickly. Each tank is usually "formed" until an average current of several hundred amperes direct current can be maintained without loss of vacuum. Generally forming can be completed in about three hours' time although the original forming of a tank just after building it may take somewhat longer.

Efficiency

The design of single-anode rectifiers with very short arc paths has resulted in a considerable reduction of the arc drop loss as compared with multi-anode tanks. It is evident that this reduction in the inherent arc drop loss of Excitron rectifiers has made possible an improvement in the overall efficiency of power rectifier equipment.

Excitron installations when operating at full load and 250 to 275 volts d-c output have an efficiency about three percent higher than that of the multi-anode tanks. On the average these efficiencies are approximately 89 and 92 percent for the multi-anode rectifiers and Excitrons, respectively. When operating at 600 volts d-c output, the Excitron shows a gain in efficiency of slightly over one percent, or from about 94 to over 95 percent.

Figures 8 and 9 are typical curves illustrating the comparative efficiencies of an Excitron rectifier and rotating type converters at 275 volt and at 600 volt service, respectively. It is apparent that the Excitron rectifier is considerably more efficient than a motor-generator set at all load factors when operated at 275 volts d-c output, but is slightly less efficient than a synchronous converter under overload conditions. However, in many 250 or 275 volt applications, such as in mining and industrial service, the load factor will average only about one-half of the rated value of the equipment, so that an Excitron rectifier will actually be the most economical type of conversion unit.

At 600 volt service, a rectifier is more efficient than a motor-generator set or a synchronous converter under all load conditions. In traction service where very light load factors prevail during long periods of the day, the high fractional load efficiency of a rectifier results in a considerable saving in power. In electrochemical service where converting equipment is generally operated continuously at full load, the rela-

tive saving in power is not so great but is nevertheless of some importance.

The power factor of an Excitron rectifier is the same as that of a multi-anode tank under similar conditions of operation. For the usual transformer connections, the power factor of mercury arc rectifiers is between 93 and 96 percent. It remains practically constant from full load down to 25 percent load. The relatively high power factor of a mercury arc rectifier exerts a corrective influence on systems supplying loads having low power factors, but a rectifier cannot furnish leading current for power factor correction.

Applicability

The development of single-anode rectifiers of the Excitron type is particularly advantageous to users of high current d-c power at voltages in the neighborhood of 250 volts direct current. In addition to providing an improvement in efficiency in comparison with multi-anode rectifiers and motor-generator sets, Excitron units are somewhat smaller in dimensions for equivalent ratings, are much lighter in weight, and can be easily installed and serviced without the use of special foundations or overhead cranes.

Other advantages include the possibility of quickly replacing one tank, if necessary, with a spare tank, and of completely overhauling and replacing a tank in service in a fraction of the time required for overhauling other types of converting equipment. A disadvantage which may be cited is that a larger amount of automatic ignition-excitation equipment is required, but this is somewhat offset by the fact that only rugged type relays, resistors, and transformers are used in this control equipment.

The advantages of single-anode rectifiers will have to be weighed against the proved reliability of multi-anode tanks over a period of time before a prediction can be made as to whether or not this new type of converter will ultimately replace multi-anode tanks for 600 volt or higher voltage service. However, for 250 volt applications the development of the single-anode rectifier is already recognized as an important advance in the power conversion field.

AT RIGHT: Prior to shipment, the contact assembly of a ruptor-equipped oil circuit breaker is inspected.

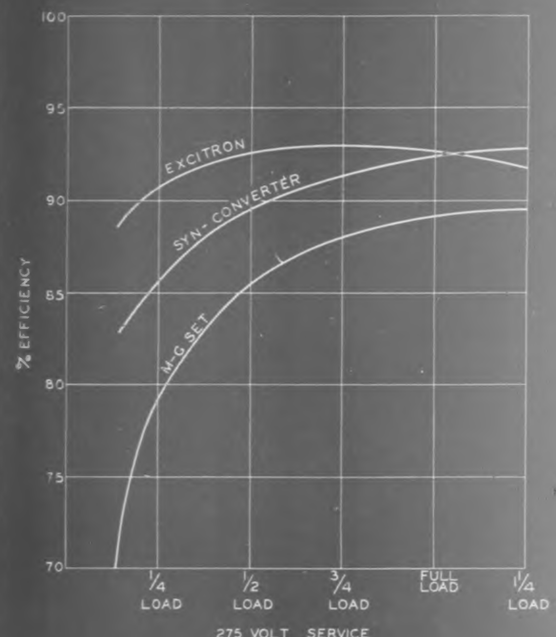


Fig. 8

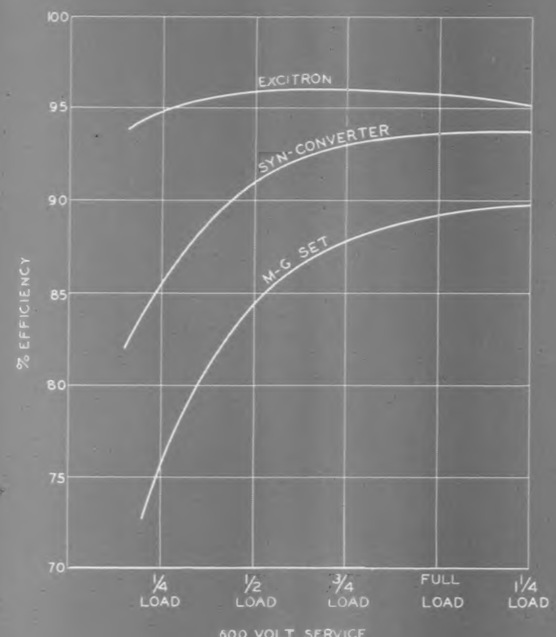


Fig. 9

ENGINEERING FUNDAMENTALS

Low Voltage Release • Low Voltage Protection
Two Wire Motor Control • Three Wire Motor Control

Motor control, in general use, is arranged so that upon loss of voltage the motor is disconnected from the line and either restarts upon restoration of voltage or remains disconnected — as determined by conditions under which the motor is operating.

The terms for the two methods, classified as low voltage release and low voltage protection, are often misused.

Low voltage release

Upon occurrence of a failure in line voltage, with the low voltage release arrangement the motor is disconnected from the line but is permitted to restart automatically when line voltage is re-established. Therefore, low voltage release can be used only in conjunction with automatic starters. Low voltage release should not be used where restarting would be hazardous to the operator working on the machine. This arrangement is, however, often used on pumps, fans, compressors and similar equipment.

An example of low voltage release is an automatic starter using magnetically operated contactors and a two-wire control connection. (See Fig. 1.) Because the inherent characteristics of a magnetically held contactor cause it to open or drop out when the voltage across the holding coil falls to approximately 75 percent of normal, the motor is disconnected from the line; but, as a result of the two-wire control connection, the motor restarts when the line voltage is restored.

When electrically operated air or oil circuit breakers of the "latched-in" type are used, the same result can be obtained by means of an undervoltage attachment on the breaker and a two-wire control connection of the master control circuit. On loss of voltage, the operation is similar to that of the magnetically held contactors as outlined above, except that the breakers are tripped by the direct action of the undervoltage attachment.

Two-wire control is essentially a system of connection that energizes the control contactor when the starting switch is closed and de-energizes the control contactor when the starting switch is open. With this connection no sealing circuit is required. (See Fig. 1.) The starting switch may be a maintained-contact push button station or a selector switch used in conjunction with a float switch, pressure switch, thermostatic switch or similar device which automatically closes its contacts when the motor is required to start and opens its contacts when the motor is required to stop.

Low voltage protection

Low voltage protection is similar to low voltage release in that when a failure of line voltage occurs the motor is disconnected from the line. The systems differ in that with low voltage protection the motor will not restart when the service voltage is restored until the operator closes the starting switch. Low voltage protection may be used on both manually and magnetically operated starters. Three-wire control is used in conjunction with an undervoltage device in

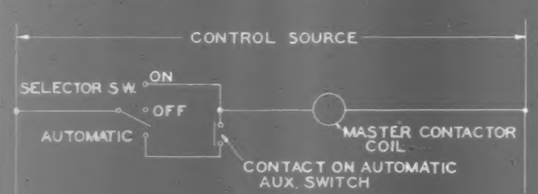


Fig. 1—Two Wire Control.

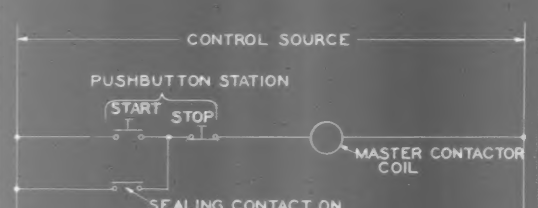


Fig. 2—Three Wire Control.

order to eliminate the restarting feature on automatic starters. (See Fig. 2.)

Three-wire control is essentially a system of connection in which the starting switch makes a momentary contact and energizes the control contactor, which in turn seals itself in through one of its own normally open contacts and a normally closed contact of the stopping device. (See Fig. 2.) The most common device for this purpose is the standard momentary contact "start-stop" push button station. Three-wire control is ordinarily furnished as a standard feature on all automatic motor starters.

Protective devices

The two general types of low voltage protection are the instantaneous and the time delay.

Instantaneous undervoltage protection may be obtained by means of a magnetically held switch which opens or closes its contact, instantaneously disconnecting the motor from the line when the voltage falls to a pre-determined value. If a latched switch such as an air or oil circuit breaker is used, the armature of the undervoltage device is connected mechanically to the trip bar of the breaker in order to trip the breaker on loss of voltage. Instantaneous undervoltage protection is standard on motor starters for 600 volts and below, but such starters can be obtained with the time delay feature.

The time delay feature is obtained by adding a delaying mechanism to the armature of the undervoltage device. It is furnished as a standard feature on motor starters for 601 volts and above. Time delay undervoltage protection is an advantage because it permits the connected equipment to "ride through" voltage dips which would otherwise shut it down. Thus the loss of time and the expense that would be involved in a complete shutdown are avoided.

On automatic starters not using a latched-in primary switch, either a time delay undervoltage relay or a time delay push button station is used. On loss of voltage, the primary switch opens and disconnects the motor from the line, as explained above with reference to instantaneous undervoltage protection. The contact of the undervoltage relay is connected so that it forms a holding circuit across the momentarily closed starting switch and opens only after a delay of several seconds (depending upon its setting).

Therefore, the action of such an undervoltage relay is to reclose the primary switch if the voltage is restored within the time setting of the relay. The time delay push button station obtains the same result in a slightly different manner. The "start" button is held closed magnetically and opens with time, on loss of voltage, through a geared escapement mechanism.

H. A. WRIGHT.

ON FOLLOWING PAGES: A 7500 kw, 750 volt motor-generator that will support a 55 in. tandem cold mill when installed. The generators, driven by a 9800 hp motor, operate in parallel.

BELOW: Machining slots for the field coils of a large turbo rotor.

SLOW SPEED REVOLUTION

J. F. Sellers

D-C ENGINEERING DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

Changes in design of d-c machines have not been as fast as the speed at which they're now travelling. But here's how steady, systematic research is bringing about greater reliability, improved performance . . . at lower maintenance costs.

Direct-current machine design in recent years has undergone no sudden change. The changes that have been made are the results of the steady development in the use of materials having better mechanical and dielectric properties and the advancement of the oscillographic study of current reversal in the armature coils in the commutating zone. The study of current collection from a commutator has also received much attention from a purely mechanical basis.

Figures 1 and 2 indicate a trend in direct-current machines which reaches almost a practical limit in these motors. Direct-current motors have been applied in steel mills to several specialized processes where the linear speed of the steel through the rolls is very high and the speed of the motors must be manipulated very quickly to prevent damage to the mill in case of bad rolling conditions. To this end the time constants of the fields have been greatly re-

Fig. 1

duced, and the inertia of the motor armatures has been lowered by using small diameters and long core lengths. Where armature core lengths would ordinarily be from 75 percent to 150 percent of the pole pitch, the ratio of the motors in this installation reaches 300 percent. The limit in smaller machines is determined by ventilation and shaft strength, while in larger machines the voltage between commutator segments usually sets the maximum ratio.

By means of low inertia armatures, the stored energy in the motors is reduced to as low as 40 percent of that which would be obtained using standard developed sizes. This large proportion between the core length and core diameter makes a heavier and usually somewhat more expensive machine, but present-day operation and development work require this type of motor in most cases. In figuring motor frames for application on a multiple-stand tandem cold reduction mill, for instance, it is necessary to calculate the inertia of working rolls, back-up rolls, roll necks, and gears—in addition to motor armature inertia—then pick the speed and armature proportion so that the accelerating torques in percent of full load value for each stand will be approximately the same.

As mentioned above, the voltage between adjacent commutator segments becomes very high on the larger

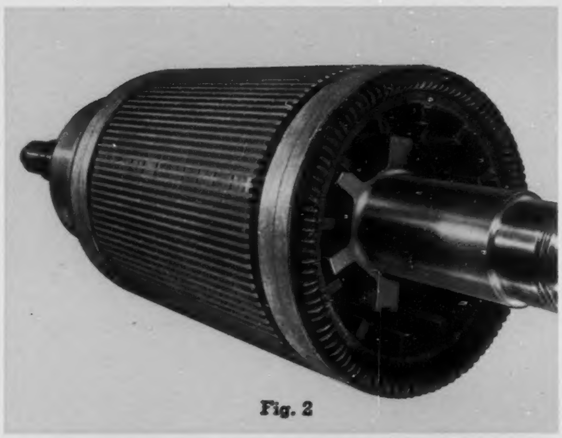


Fig. 2

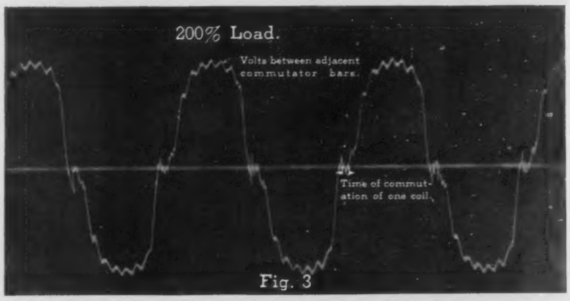


Fig. 3

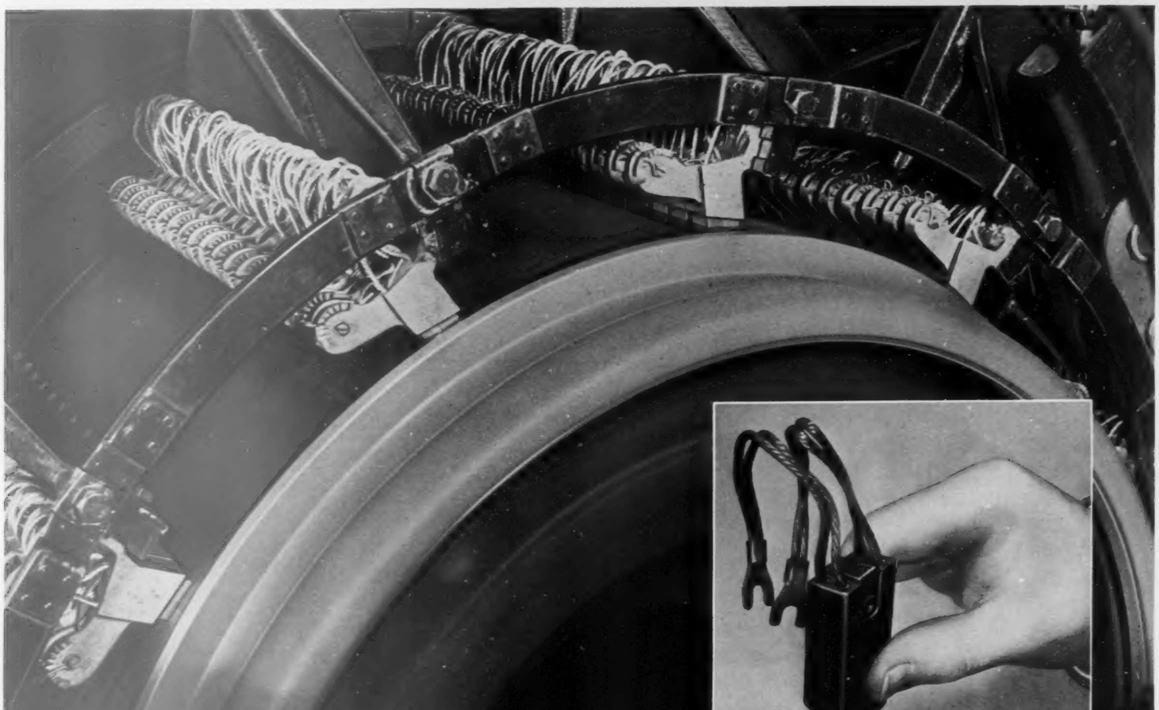


Fig. 4

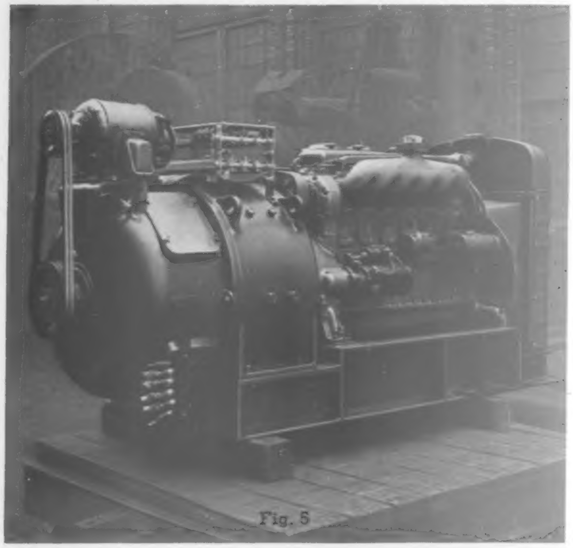


Fig. 5

sizes of low inertia motors, and exceptionally wide mica between segments is necessary. The compensating pole face windings must be designed with extreme care in order to neutralize the armature winding properly. Fig. 3 shows the flux distribution, indicated by the instantaneous voltage between commutator segments, of a large machine built recently with low inertia armature design.

Smooth riding

There has been one development in the past two years which has been the only answer found to correct a certain type of trouble encountered in the operation of large and small commutators. Some machines are quite sensitive to the surface smoothness of the commutator. To reduce this sensitivity, changes in the grade of brush have been tried in many cases, but the condition usually persists.

A simple solution to the problem is illustrated in Fig. 4. An ordinary brush is cut into two sections. A metal "A" clip is attached to the long portion and the shunts are attached to both portions. Without any mechanical changes being required, this combination brush will fit into, and operate in, a standard box-type holder. The increased modulus of elasticity of this combination as compared to a solid brush provides a much smoother riding characteristic.

The satisfactory results of this divided brush have been so evident that its use has been rapidly increasing on large d-c machines. The high cost and maintenance requirements of a tandem brush holder are eliminated; yet its good commutating and riding properties are retained. This divided brush will not correct electrical maladjustments, however, and in changing from a solid brush to a divided brush it is usually necessary to weaken the interpole field strength 10 to 20 percent by increasing the interpole air gap. The weaker interpole requirement of a divided brush is in itself an indication of the corrective commutating effect of this type of brush arrangement.

Commutator polish

A problem now engaging much study and experimentation in various brush applications is the breaking through of the normal brown polish on the commutator surface in one or more brush tracks around the periphery of the commutator. The streaks are either a light brown or polished copper color, and sometimes the track is finely threaded. This condition apparently occurs regardless of the manufacturing processes of the machine or the brushes, and often one of a pair of commutators of duplicate machines and brushes will develop streaks while the other will not.

The condition does not in general come with only high or only low speed commutators, but it does seem to be more prevalent with low current density in the brushes. Machines with slight pin sparking seldom develop such streaking. The brushes that are the most successful in overcoming this condition are those which produce a fairly heavy commutator film. On the other hand, this type of brush is usually not so good if high current densities are encountered during some load cycles.

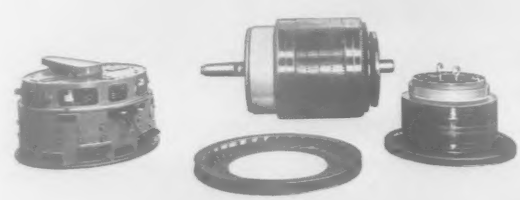


Fig. 6

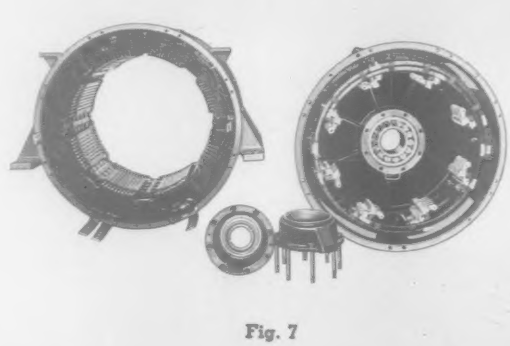


Fig. 7

Glass insulation

For some time d-c machines have been designed with glass-insulated shunt field wire, and the use of glass-insulated wire on field coils is now well established. Glass-insulated armature coils are now being applied in selected applications to observe the results under various operating conditions. Fig. 5 shows a generator for diesel electric locomotive application in which temperatures of 120 C are encountered. This generator has glass-insulated field coils and almost complete glass insulation on the armature coils. The armature winding is completely sealed in by giving the completed armatures two dippings and bakings in high temperature-resisting insulating varnish.

No difficulty has been experienced with any glass-insulated machine to date, but all such installations are being observed for the effect of vibration, temperature, and shock on the insulation and the effect of aging of the varnish treatment on the glass tape.

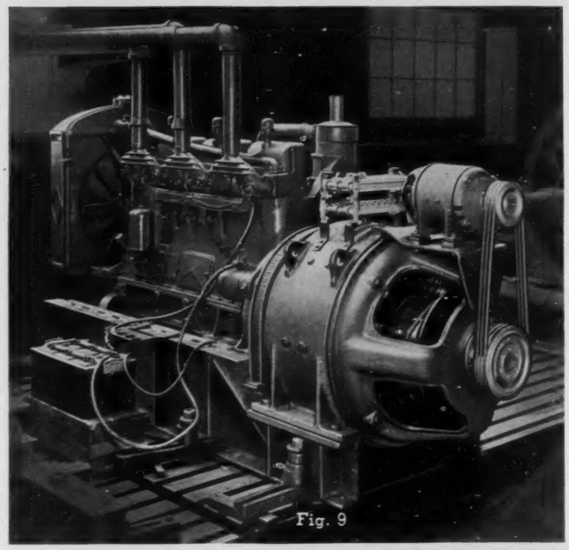


Fig. 9

Electric locomotives

The application of d-c machines to electric locomotives has been one of the main factors in the development of high temperature insulation, high permeability steel castings and laminations, with the resulting increase in output per pound of material. The generator unit for diesel electric application, shown in Figs. 6 and 7, weighs 58 percent of a standard industrial unit of the same kw output. One of two power units installed in a 40-ton switching locomotive is shown in Fig. 9. Three locomotives with this type of power source are in operation, and from the experience gained from the manufacture and operation of this equipment a fourth locomotive with engines of 50 percent higher speed and horsepower output is being built.

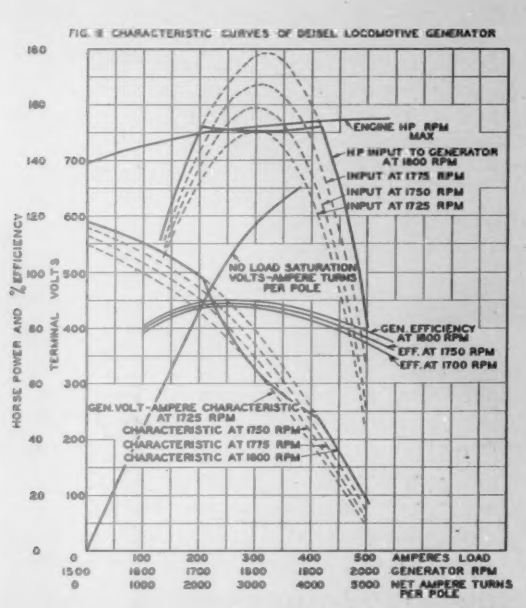


Fig. 8

Figure 8 illustrates the characteristic curves of this engine-generator unit. Almost 75 percent of the normal operating range of the locomotive speed is covered by practically rated engine horsepower. This is accomplished by the use of a differential series field, heavy self-excited shunt field, and a light separately excited shunt field, together with automatic switching of motors from series to parallel connection. The separate excitation is taken from the constant voltage battery charging generator which is part of the engine equipment. This generator is completely insulated with Class "B" insulation and is expected to operate at about 100 C.

Summary

The simplicity of manipulation of a large d-c motor with separate or constant voltage source has caused almost the entire elimination of the conventional Kramer or Scherbius drives for new installations. Lower maintenance of straight d-c equipment has also brought about this condition. The ease of changing the inherent speed characteristic of d-c motors has been an important factor in the continued and ever-expanding use of this type of machine, especially in steel mills. Advantage has been taken of every improvement in materials to give greater reliability and improved performance in d-c equipment.

STREAMLINING PATENT PROSECUTION

D. Journeaux

PATENT ATTORNEY • ALLIS-CHALMERS MANUFACTURING COMPANY

Tear-drop automobiles, streamlined locomotives, sleek stratoliners . . . all are functionally designed for greater speeds. To expedite the granting of patents, Congress passes legislation that streamlines patent prosecution to this fast-moving era.

Year in and year out, Congress gives consideration to various bills relating to patents and designed primarily to modify either the procedure for the grant of patents or the extent of the advantages granted to patentees. Although these bills are sufficiently numerous to cause Congress to maintain a Committee on Patents for their study, relatively few of them are enacted. Last year, however, several bills were passed requiring inventors to show greater diligence in their efforts to obtain patents, and others may be enacted in the near future.

This legislation is not the result of a concerted effort by the administration or by hostile lobbies to harass defenseless inventors. Rather, it is an attempt to bring present Patent Office practice more closely into accord with the intents of the Constitution, as amplified and clarified by early acts of Congress and by the decisions of the courts.

Patent system in interest of the public

It is true that this revision of the patent system does restrict some of the rights of inventors seeking patent protection. Restrictions were in order, however, because changing social and economic conditions had rendered the unwise exercise of those rights burdensome to the public at large. This may not appear to call for reform, but it must be remembered that the primary concern of Congress is the welfare of the people. In accordance with this principle, and contrary to what inventors may like to believe, our patent system was not established with the primary purpose of rewarding worthy inventors. It aims rather to induce inventors to make their inventions available to the public for a compensation sufficient to provide an incentive for making these inventions.

The basis for the American patent system was created by the Constitution, which provides that: "The Congress shall have power . . . to promote the progress of science and useful arts, by securing for limited times to . . . inventors the exclusive right to their . . . discoveries." On this authority, Congress in 1790 enacted the first statute providing that inventors could be granted patents for inventions "not before known or used." In 1829 the Supreme Court had occasion to rule the statute to mean that an invention, to be patentable, should not be known or used by the public in general, as distinguished from those aiding the inventor in the development of his invention.

In the same decision, the philosophy of the patent system was expressed as follows: "While one great object was, by holding out a reasonable reward to inventors and giving them an exclusive right to their inventions for a limited period, to stimulate the effort of genius; the main object was 'to promote the progress of science and useful arts'; and this could be done best by giving the public at large a right to make, construct, use and vend the thing invented, at as early a period as possible; having a due regard to the rights of the inventor." It is evidently in the public interest to induce inventors to patent their inventions as soon as possible after their conception in order that the patents may expire as early as possible.

Patent applications

To make sure that, after expiration of the patent, the public will be able to reap the benefit from the invention, the inventor is required to file "a written description of the same, and the manner and process of making, constructing, compounding, and using it, in such full, clear, concise, and exact terms as to enable any person skilled in the art or science to which it appertains, or with which it is most nearly connected, to make, construct, compound, and use the same; and in case of a machine, he shall explain the principle thereof, and the best mode in which he has contemplated applying that principle."

The inventor may receive patent protection only on as much of his invention as he disclosed in the

AT LEFT: On the boring mill — the stator frame for a high speed induction motor.

prescribed manner; and it is, therefore, generally in his interest to describe his invention in considerable detail. In return for his contribution to the public weal the inventor is granted, for the term of seventeen years, "the exclusive right to make, use, and vend the invention or discovery." This grant is but a means to an end—namely, the disclosure of the invention to the public. The grant is rather misleading and was better expressed by the Supreme Court as "the right to exclude everyone from making, using, or vending the thing patented, without the permission of the patentee." In fact, the inventor himself has naturally the right to make, use, and vend his invention unless, as often happens, he is prevented from doing so by patents on related inventions granted to others.

Public use period

The evolution of industry and of its methods of exploiting inventions, including their publication, has led Congress to make concessions to inventors. In particular, the statutes were amended at one time to permit the grant of a patent to the first inventor on inventions having been in public use or on sale in this country for as long as two years before their application date or having been described in a printed publication anywhere during that time.

This procedure gives the inventor time to test his invention in commercial operation, to discover and correct its defects, and eventually to patent his invention in its improved form. In this manner the inventor may delay filing his patent application until long after completion of his invention. In so doing he also delays the expiration date of his patent while enjoying practically the same advantages as if he had filed his application as soon as the invention was made. While a public use period of two years was probably in harmony with the rate of development of industry during the last century, it may be considered unduly long now that the tempo of industry has quickened considerably.

Congress therefore revised the statute, and beginning August 5, 1940, any patent application on an invention in public use in this country will have to be filed within one year from the date of its first public use. The same applies to inventions placed on sale in this country or described in a printed publication anywhere. It should be noted that public use includes private use and commercial use but excludes secret or experimental use. Use for commercial production in a factory to which the public does not have access constitutes public use.

Response to patent office actions

After a patent application is filed, the patent is not granted as a matter of course, since the application must first be examined quite critically. Usually the examination uncovers some defect or informality, or the examiner wants in the record the applicant's argument as to some point, of which the applicant is informed by the Patent Office.

At one time an applicant was given two years either to overcome the objections of the Patent Office or else to remove the grounds for objection. This procedure may have been reasonable when a letter took months to travel from coast to coast, but it also delayed the grant of the patent and hence also its impatiently awaited expiration. The time allowed an inventor to respond to the rejections of the Patent Office was therefore gradually reduced as mail service became faster. As recently changed, the law provides that, at the discretion of the Commissioner of Patents, the Patent Office may require a response within any period from thirty days to six months.

In order to reduce the number of times that the application has to be examined, the Patent Office is also trying to limit the number of amendments made by an applicant to his application. This would reduce the amount of work done in the Patent Office at public expense and hasten the grant of patents. Of course, an abridged prosecution of a patent application may not always give an unwary inventor the opportunity of securing all the patent protection available to him. It must be said, however, that the gradually evolved and solidly entrenched practice of endlessly amending a patent application may rightly be viewed with alarm both by the Patent Office and by the public.

Renewals abolished

Another practice which permitted delay in the grant of a patent was the renewal. Under this practice an application could be filed and repeatedly amended until its claims were found allowable. Upon timely payment of a renewal fee, the prosecution could be started over again, often for the primary purpose of securing additional claims which had not been thought of earlier. Naturally, this delayed the issuance of the patent by a considerable length of time.

While under the amended law renewals will no longer be obtainable, it seems that their purpose can still be accomplished equally well, with the same resultant burden on the public, by forfeiting the allowed application after filing another application in its stead. This so-called continuing application reproduces the specification and claims of the allowed application with the addition of whatever other claims the applicant wishes to secure. Some day, in the interest of the public, this practice too may be banned by Congress.

Copying claims from patents

Although all inventions must be new to be patentable, most of them are more or less natural modifications or improvements of old inventions or of devices in common use. It is not surprising, therefore, that many similar inventions are made almost simultaneously by two or more independent inventors. One who has reason to believe himself to be the first inventor of an invention sometimes sees that a later but more alert inventor has secured a patent for the same invention. The self-presumed first inventor may then

claim the invention for himself in a pending or new application disclosing it, by copying at least one appropriate claim from the patent. Now he must, however, do so within two years from the issuance of the patent.

Beginning August 5, 1940, this period will be reduced to one year to force an earlier determination as to whether the patentee or the applicant is the first inventor and, if the applicant is first, to hasten the eventual issuance of his patent. This change in the law should not be a burden to inventors who, at least in the United States, may see the substance of all U. S. patents in the Patent Office Gazette within one week from their issuance.

Another recent act of Congress purports to expedite the determination of first inventorship between competing inventors by abolishing appeals in interference cases within the Patent Office.

While the burden placed on the public by lengthy prosecution of patent applications has been recognized for a long time, the difficulty is to find equitable remedies for it and to convince the majority in Congress that they should be applied. This has apparently prevented any action being taken for many years. Although the changes made last year are not sensational, they are far-reaching in that they affect every application filed in the Patent Office. Their enactment may even have been possible only because of their apparent moderation.

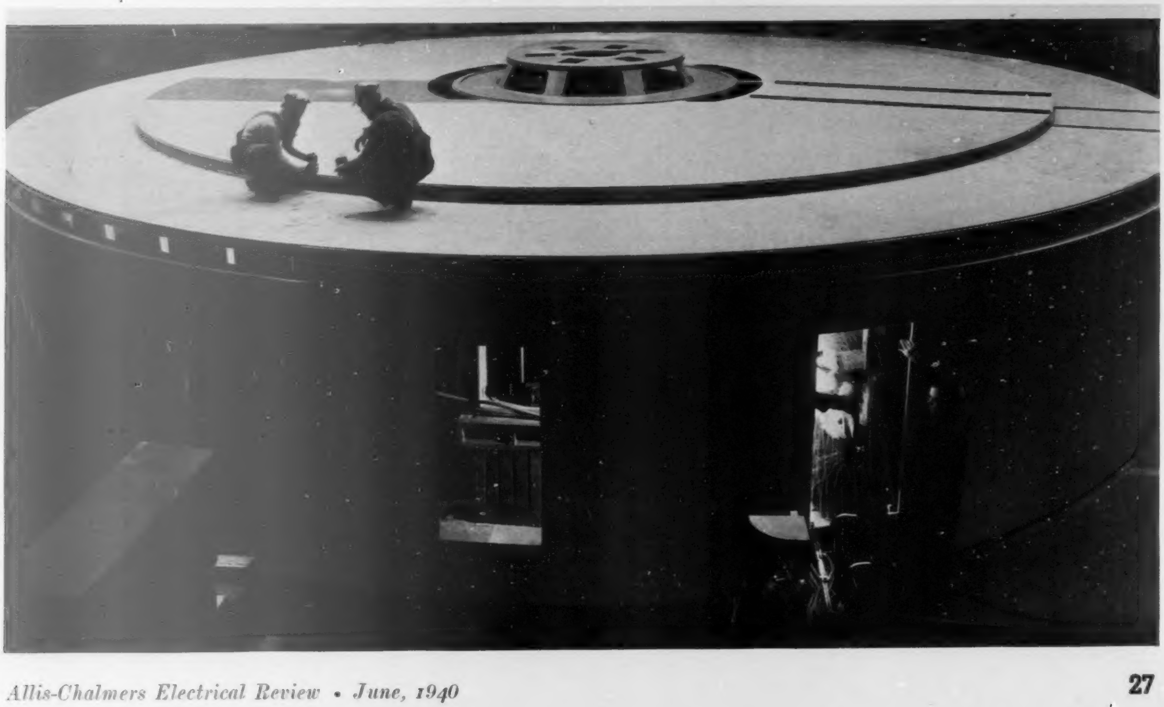
More changes probable in future

Further changes may be introduced in the patent laws now that a program of reform has been started. Action should be expected as a result of a recent Supreme Court decision which pointed out a glaring inconsistency in the law.

As has happened occasionally, an invention may be made independently by an American inventor and a foreign inventor. The foreign inventor, for example, may be first to conceive and reduce his invention to practice, both acts taking place abroad. The domestic inventor, however, may have reduced his invention to practice before the effective date of the foreign inventor's United States patent application. Under the present statutes, if the domestic inventor applies for a United States patent, the Patent Office will declare him to be the first inventor, and he may receive a valid patent. If, however, the domestic inventor fails to apply for a United States patent, the foreign inventor may receive one and sue the domestic inventor for infringement if the latter is exploiting the invention in this country. The courts will then be bound to recognize, upon evidence being submitted, that the foreign inventor is the first inventor and that his patent is valid.

The Supreme Court broadly hinted that such a situation called for revision. A bill recently introduced in Congress would prevent a foreign inventor from availing himself of any of his activities abroad prior to the filing of his patent application abroad or in this country in order to establish conception and reduction to practice of his invention. This bill, if enacted, will render uniform the determination of the dates of foreign inventors in Patent Office proceeding and in the courts. But perhaps Congress should not be expected to actively take up patent matters in a year of international turmoil and of a presidential election.

The 45-foot housing for a water wheel generator.



TRANSFORMER TEAMWORK

W. C. Sealey

TRANSFORMER DIVISION • ALLIS-CHALMERS MANUFACTURING COMPANY

Teamwork brings greater results than uncoordinated efficiency. And transformers . . . like humans . . . must have definite characteristics in order to work together . . . particularly when you want to operate them in parallel.

When two transformers are operated in parallel, the terminals of like windings are connected to each other as shown in Fig. 1. With these connections, since the terminals of the windings are solidly tied together, the primary voltages of both transformers must be the same and the secondary voltages must be the same. If necessary, current will flow through the paralleled windings and produce the necessary impedance voltages to attain this voltage relation.

Successful parallel operation occurs when (1) these circulating currents are low in value, and (2) the load division between transformers is satisfactory so that the desired total load can be carried without overloading either transformer.

The factors affecting parallel operation of two-winding transformers are:

1. Voltage rating
2. No-load ratio of transformation
3. Transformer impedance
4. Ratio of resistance to reactance

For ideal operation, the values of these factors should be the same for the transformers being paralleled in accordance with the following explanation:

1. The transformers should either have the same voltage rating or be capable of being safely re-rated to operate at the required voltage.

2. The ratio of transformation at no-load should be the same for both transformers so that no change in currents or voltages would occur if the transformers were being excited on their primary side and the secondary terminals were suddenly connected together.

3. When the transformers are rated on the same voltage and their respective kva ratings for the same temperature rise, the percent impedance should be the same for both transformers. (The percent impedance is equal to 100 times the impedance voltage required to force full load current through one winding with the other winding short circuited divided by the rated voltage of the first winding.)

4. The ratio of the resistance component of the impedance to the reactance component of the impedance should be the same for both transformers.

Voltage rating

Since transformers to be paralleled must be connected to the same lines, either they must have the same voltage ratings or it must be possible to re-rate them so that their voltage ratings are the same. Based on the re-rated voltage, the transformers must have safe values of insulation strength, exciting current, rated kva load and temperature rise. Because of changes in these factors it is seldom that a great change in voltage is made when transformers are re-rated.

No-load ratio of transformation

If the no-load ratio of transformation of two paralleled transformers is exactly the same, there will be no current circulating between them at no-load. If the two paralleled transformers have different voltage ratios, current will circulate between them even at no-load. This current is equal to the difference in secondary no-load voltages (with the same primary voltage applied) divided by the sum of the impedances of the two transformers.

$$I = \frac{E_1 - E_2}{Z_1 + Z_2} \quad (1)$$

where I is the current in the secondary windings of the transformers at no-load

E_1 is the no-load secondary voltage of transformer No. 1 when the primary voltage is E_a

E_2 is the no-load secondary voltage of transformer No. 2 when the primary voltage is E_a

Z_1 is the impedance of transformer No. 1 on the secondary side

Z_2 is the impedance of transformer No. 2 on the secondary side.

All quantities are vector quantities.

If E_1 and E_2 are expressed in volts and Z_1 and Z_2 in ohms on the secondary side, the current I will be in amperes in the secondary winding. If E_1 and E_2 are expressed in percent of E_1, and Z_1 and Z_2 in percent of E_1 on the same kva base, the current I will be expressed as a fraction of the full load current of transformer No. 1. (The primary voltage, E_a, expressed in percent=100.)

The primary current in transformer No. 1 is equal to $\frac{E_1}{E_a}$ I; in transformer No. 2 the primary current is equal to $\frac{E_2}{E_a}$ I. The line current is equal to the difference between the primary currents:

(2) Line current $= I\,\dfrac{(E_1-E_2)}{E_a}$

Example

Given: Two single-phase transformers operating in parallel with the following characteristics:

	1	2
Transformer No.	1	2
Kva	500	500
High Voltage	2300	2300
Low Voltage	465	460
% Resistance based on LV	1%	1%
% Reactance based on LV	4.9%	4.9%
Rated HV amp	217	217
Rated LV amp	1075	1087

Required: The circulating current at no-load.

<u>Solution using impedance in ohms:</u>

1. The impedance of transformer No. 1 in ohms is equal to $\frac{465\,(.01+j\,.049)}{1075} = .00432+j\,.0212.$

The impedance of transformer No. 2 in ohms is equal to $\frac{460\,(.01+j\,.049)}{1087} = .00423+j\,.0207.$

The circulating current $I=\dfrac{E_1-E_2}{Z_1+Z_2}$

$$= \frac{465-460}{.00432+j\,.0212+.00423+j\,.0207}$$

$$= \frac{5}{.00855+j\,.0419} \times \frac{.00855-j\,.0419}{.00855-j\,.0419}$$

$$= 23.4-j\,114.5 \cong 117 \text{ amp at } 20\% \text{ power factor.}$$

Since the rated low voltage current of transformer No. 1 is 1075 amp, the no-load circulating current is equal to $\frac{117\times100}{1075}$ or 10.9 percent of the rated current of transformer No. 1.

The high voltage line current due to this circulating current is equal to

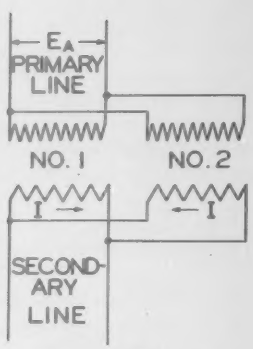
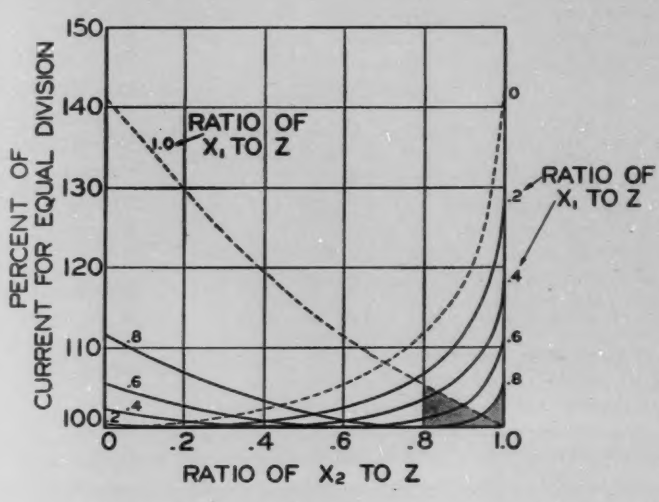


Fig. 1—Two Transformers in Parallel.



R_1 is the Resistance of Transformer No. 1.
X_1 is the Reactance of Transformer No. 1.
X_2 is the Reactance of Transformer No. 2.
Z is the Impedance of Transformer No. 1 & 2.

Fig. 2—Current Division between Two Transformers having the same kva Rating and Impedance but Different Reactances.

$$I\frac{(E_1-E_2)}{E_a}=117\frac{(465-460)}{2300}=2.54\text{ amp.}$$

This is equal to $\frac{.254\times 100}{217}$ or 0.12 percent of the full load current of transformer No. 1.

(Even though the circulating current between the transformers is 10.9 percent, the current which flows in the line is equal to the difference between the currents in the primaries of the two transformers, or only 0.12 percent of the line current of one transformer.)

Solution using impedance in percent:

2. The impedance of transformer No. 1 in percent is equal to:

$$1+j\,4.9$$

The impedance of transformer No. 2 in percent based on 465 volts low voltage is equal to

$$(1+j\,4.9)\left(\frac{460}{465}\right)^2=0.98+j\,4.79.$$

The voltage $E_1=100\%$;

the voltage $E_2=\frac{460\times 100}{465}=98.925\%$.

The circulating current $I=\frac{E_1-E_2}{Z_1+Z_2}$

$$=\frac{100-98.925}{1+j\,4.9+.98+j\,4.79}=\frac{1.075}{1.98+j\,9.69}\times\frac{1.98-j\,9.69}{1.98-j\,9.69}$$

$=.0218-j\,.1066\cong 0.109\cong 10.9\%$ of the rated current of transformer No. 1.

The high voltage line current due to this circulating current is equal to $I\,\frac{(E_1-E_2)}{E_a}$

$=10.9\,\frac{(100-98.925)}{100}\cong 12\%$ of the full load current of transformer No. 1.

It is extremely important that the no-load ratios of paralleled transformers should be as close to the same value as possible. In the example, the difference in the no-load secondary voltages was only 1.075 percent when the same primary voltage was applied. This was sufficient to cause 10.9 percent circulating current in the transformer windings. If the difference in ratio had been equal to 10 percent, the circulating current would be equal to $\frac{10}{1.075}\times 10.9=101$ percent of full load current in the transformer windings at no-load. That is, the transformer windings would be slightly overloaded at no-load and consequently would be unable to carry any useful load without exceeding the transformer rating.

However, a small no-load circulating current does not interfere with satisfactory operation, since generally the load power factor is high and the circulating current power factor is low. In the previous example, with 100 percent load at 100 percent power factor, the total current in the secondary of transformer No. 1 equals $1075+23.4-j\,114.5=1098.4-j\,114.5\cong 1102$ amperes or 102.5 percent of full load current. Under these conditions 10.9 percent circulating current increases the load current only 2.5 percent.

The maximum difference in ratio which can exist and which will not interfere with satisfactory operation depends entirely upon whether or not the currents as given by equations (1) and (2) exceed permissible values. If the transformers will safely carry the required load, satisfactory operation will be secured.

Transformer impedance

If two transformers are paralleled, the load will divide between them so that the impedance drop due to load current will be the same for each transformer.

A different way of stating the rule for the division of current is: "The currents will divide between two paralleled transformers in an inverse proportion to their impedances." When both transformers have the same ratio of transformation, if expressed in ohms, the impedances must be on the same voltage base; and, if expressed in percent of rated voltage for a given kva, the impedances must be on the same voltage and kva base.

The load which can be carried by two transformers in parallel for a given temperature rise of the transformers may be found as follows when the kva rating of each for the temperature rise and the impedance of each transformer corresponding to its kva rating are given. The transformer with the lowest percent impedance can carry its kva rating. The load on the other transformer will be inversely proportional to the ratio of its impedance to the impedance of the first transformer. For example, transformer No. 1 is rated 1000 kva, 55 C rise, 6 percent impedance.

Transformer No. 2 is rated 500 kva, 55 C rise, 5 percent impedance.

Transformer No. 2 will carry 500 kva for 5 percent impedance drop.

Transformer No. 1 will carry $1000\times 5/6$ kva, or 833 kva for 5 percent impedance drop.

The load which can be carried without exceeding 55 C rise of either transformer is $500+833$ kva$=$ 1333 kva.

Below is given a tabulation for several different sizes of transformers connected in parallel.

Example No.		2	3	4
Transformer kva	No. 1	1000	1000	1000
	No. 2	50	50	50
Impedance	No. 1	5%	5%	5%
	No. 2	2%	10%	5%
Safe load when paralleled	No. 1	400	1000	1000
	No. 2	50	25	50
Total Safe Load		450	1025	1050

Note that for example 2 the total safe load is less than for one transformer operating alone. This is because the smaller transformer has a much lower impedance and kva rating.

For example 3 the smaller transformer has the higher impedance, so parallel operation is possible even though the impedances are widely different. The maximum output of a bank is obtained when all transformers have equal percent impedances on their rated kva, as in example 4. However, if the impedances are different, it is more advantageous for the smaller transformer to have the higher impedance. The general rule may be stated slightly differently; namely, "For parallel operation each transformer should be re-rated by reducing its kva rating until its percent impedance is equal to the lowest percent impedance of any paralleled transformer." In example 2, the re-rated kva of the 1000 kva transformer is $2/5 \times 1000 = 400$ kva.

When the ratios of transformation are the same, there will be no circulating current at no-load (neglecting magnetizing current), and the current in each winding may be determined from the impedances alone. When the ratios of transformation are unlike, the circulating current at no-load may be calculated as previously described, and the load current division between transformers calculated using the impedances in ohms on the secondary side with the same voltage applied to the high voltage winding of each transformer. The load current will divide between the two transformers in an inverse proportion to these impedances in ohms. The total current in the windings is equal to the sum of the load currents and the no-load currents.

For precision work, the impedances should be given as complex numbers or vector quantities. However, this degree of precision is seldom necessary for practical use when both transformers have the same ratio of transformation. Sufficient accuracy is usually obtained by expressing the impedances as a plain number in percent or in ohms.

Ratio of resistance to reactance

In the foregoing examples, a ratio of resistance to reactance which was the same for all transformers was assumed. While this assumes in-phase currents in all transformers, it is generally a relatively unimportant item except in the case of transformers with very low impedances and for small transformers where the percent resistance may be as large as the percent reactance.

These relations are shown on the chart of Fig. 2. This chart covers all possible cases for two-winding transformers of equal kva ratings and equal impedances. For power transformers and large distribution transformers, the ratio of the reactance to the impedance seldom is less than 0.8. (This corresponds to a ratio of resistance to reactance of less than 0.75.) Consequently, the portion of the chart which applies to these transformers is the small shaded portion. It is evident from this curve that the ratio of resistance to reactance has little effect in the case of power transformers. (If the letters R and X are interchanged on this diagram, the diagram will be correct to show the current division for different percent resistances of the transformers.)

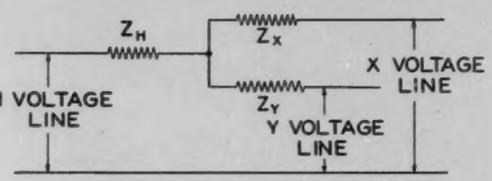


Fig. 3—Equivalent Circuit of a 3-Winding Transformer.

Three-winding transformers

The general principles applying to the parallel operation of three-winding transformers with other three-winding transformers or with two-winding transformers are the same as those for the paralleling of two-winding transformers, but the complexity of their application is increased by the addition of the third winding. As before, all winding terminals which are solidly tied together must have the same voltage across them, and any necessary current will flow to produce the necessary impedance drops to attain this voltage relation.

The equivalent circuit which is used for a three-winding transformer is shown in Fig. 3. If the no-load ratios of transformation are not the same, the circulating currents present at no-load can be calculated as described for two-winding transformers but using this equivalent circuit.

The division of the load current superimposed on this exciting current can also be determined by using this equivalent circuit and noting that the voltage drop due to load current from the supply winding to the terminals of each of the other windings must be the same for each transformer.

Paralleling three-winding transformers

The ideal conditions for parallel operation of two three-winding transformers is obtained when the transformers have

1. The same voltage rating
2. The same no-load ratios of transformation
3. The same percent impedances based on their respective kva ratings for the same voltage and temperature rise
4. The same ratio of resistance to reactance in each branch of the equivalent circuit
5. "Similar" kva ratings of the several windings

To have "similar" kva ratings, the several kva ratings of the windings of the second transformer must be equal to the several kva ratings of the first transformer multiplied by the same factor for all windings.

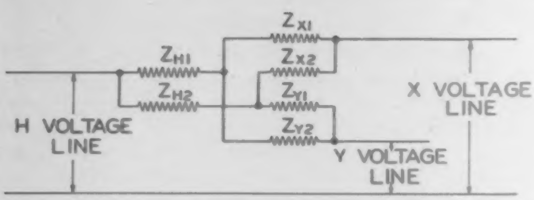


Fig. 4—Equivalent Circuit of Two 3-Winding Transformers in Parallel.

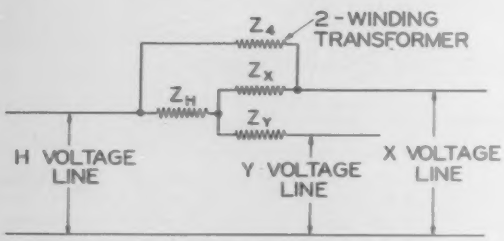


Fig. 5—Equivalent Circuit of a 3-Winding and a 2-Winding Transformer in Parallel.

For example, if a transformer has windings with full load ratings as follows:

H Winding 20,000 kva
X Winding 10,000 kva
Y Winding 15,000 kva

and a transformer to parallel with it is to be built having an H winding of 10,000 kva, then since this winding has one-half the kva rating of the H winding of the first transformer, each of the other windings should have a rating equal to one-half the kva rating of the similar winding in the first transformer; and consequently the rating of the X winding must be 5000 kva, and the rating of the Y winding must be 7500 kva.

The following tabulation shows four transformers having similar kva ratings to each other:

Transformer No.	1	2	3	4
Kva H Winding	20000	10000	1000	600
Kva X Winding	10000	5000	500	300
Kva Y Winding	15000	7500	750	450

The following is another example of four transformers which are not similar to the above transformers, but which are similar to each other:

Transformer No.	1	2	3	4
Kva H Winding	5000	15000	500	1000
Kva X Winding	5000	15000	500	1000
Kva Y Winding	3333	10000	333	667

When transformers that do not have similar kva ratings of their respective windings are paralleled, equal division of load between windings may be possible for certain loads; but equal division will not be obtained for all loads. If, as is frequently the case, loads to be carried can be restricted to those in which equal division is obtained, or if the loads to be carried do not overload either transformer, it is obvious that operation will be satisfactory without fulfilling the ideal conditions.

Satisfactory parallel operation for the given operating conditions may result even when these ideal conditions are not present, as for example where loads are very light during unbalanced conditions of operation. In this example, where the load is very light safe operation is secured because no transformer will be overloaded even if the load does not divide in proportion to the kva ratings of the windings.

Where the ideal relations do not exist and parallel operation is desired between three-winding transformers, the load division can be calculated (using the equivalent circuit for the three-winding transformer, Fig. 4) for the loadings to which the bank will be subjected. If these loadings do not overload any transformer, such parallel operation may be performed successfully. In the final analysis, the principal requirement for parallel operation is that no transformer be subjected to loads in excess of safe values.

Paralleling three-winding with existing two-winding transformer

When it is desirable to construct a three-winding transformer to parallel with an existing two-winding transformer, or vice versa, or to parallel existing two- and three-winding transformers, current division in proportion to the kva ratings of the windings for all possible operating conditions cannot be obtained. This case may be treated as a special case of parallel operation of two dissimilar three-winding transformers where the impedance of one winding equals infinity.

Since ideal load division cannot be obtained for all loads, the load division should be calculated for all loads which will exist in order to determine whether or not either transformer will be overloaded. Occasionally it is desirable to design a transformer so that the impedance of one leg of the equivalent circuit is equal to zero or so that it has a negative value. Within certain limits, values such as these can be obtained by design. Of course, not more than one leg of the impedance diagram can have a zero or negative value, and the impedance between terminals must always have a positive value. The following examples show how kva ratings and impedances can be selected for specific cases, using the equivalent circuit of Fig. 5.

Example—

PARALLEL OPERATION OF 3-WINDING WITH EXISTING 3-WINDING TRANSFORMER

Given a three-winding transformer:

H winding 10,000 kva
X winding 5000 kva
Y winding 5000 kva

$$\begin{array}{ll} \text{Impedance} & \left\{ \begin{array}{lll} \text{H–X} & (Z_1) & 8\% \\ \text{H–Y} & (Z_2) & 8\% \\ \text{Y–X} & (Z_3) & 6\% \end{array} \right. \\ \text{on 10000} & \\ \text{kva base} & \end{array}$$

Required: The impedance of a 5000 kva two-winding transformer to operate in parallel with the H and X windings.

Method: $Z_H+Z_X=Z_1$

$Z_H+Z_Y=Z_2$

$Z_Y+Z_X=Z_3$

Solving: $Z_H=\dfrac{Z_1+Z_2-Z_3}{2}=\dfrac{8+8-6}{2}=5$

$$Z_X=\frac{Z_1+Z_3-Z_2}{2}=\frac{8+6-8}{2}=3$$

$$Z_Y=\frac{Z_2+Z_3-Z_1}{2}=\frac{8+6-8}{2}=3$$

If the 5000 kva two-winding transformer is to divide the load equally with the three-winding transformer when the three-winding transformer is fully loaded, its impedance drop from H to X must be the same as the impedance drop of the fully loaded three-winding transformer from H to X or $5+\frac{3}{2}=6.5\%$ on a 5000 kva base. Under these conditions the two transformers will divide the loads equally, all windings will be fully loaded simultaneously and satisfactory parallel operation will be secured. The kva which can be transformed from H to X will be 10,000 kva. If now the Y load is removed from the three-winding transformer, the impedance drop through the three-winding transformer on a 5000 kva base from H to X is equal to $\frac{8}{2}=4\%$.

The two-winding transformer with an impedance of 6.5 percent will now be paralleled with the three-winding transformer with an impedance of four percent. In order not to overload the three-winding transformer, the two-winding transformer must be de-rated to $\frac{4}{6.5}\times 5000=3080$ kva. The kva which can be transformed from the H to the X winding without either transformer being overloaded (with the Y winding idle) is $5000+3080=8080$ kva. If light load on the X winding coincides with light load on the Y winding, these transformers will parallel satisfactorily.

If the two winding transformer were designed to have four percent impedance so that it would divide the load equally with the Y winding idle, it would be overloaded when the three-winding transformer was fully loaded. Under these conditions the four percent impedance, two-winding transformer would be paralleled with the three-winding transformer having a 6.5 percent drop from the H to the X windings with full load. With 5000 kva on the Y winding, the drop in the H winding is 2.5 percent. The X winding must be de-rated so that the total drop from H to X is four percent. Its rating then is $\frac{4-2.5}{8}\times 10{,}000=1875$ kva.

The total load which can be carried on the X line with the Y line carrying 5000 kva is $5000+1875$ or 6875 kva.

It is possible that an intermediate value of impedance between four percent and 6.5 percent would be chosen for the 5000 kva transformer, or if it were necessary to carry 10,000 kva on the X line under all conditions, it might be necessary to use a two-winding transformer larger than 5000 kva. Such a transformer, designed so that the bank delivers 10,000 kva on the X winding from the H winding under all conditions, must have not over four percent impedance at 5000 kva to parallel with the Y winding idle.

With the Y winding fully loaded and if Z_5 is the impedance drop of the two-winding transformer when delivering 10,000 kva to the X line, the total kva delivered to the X line $=\frac{Z_5-2.5}{8}\times 10{,}000+\frac{Z_5}{4}\times 5000$ $=10{,}000$ kva, or $Z_5=5.25\%$.

Thus a two-winding transformer with a kva rating of $\frac{5.25}{4}\times 5000=6560$ kva and an impedance of 5.25 percent of its rating would operate in parallel with the three-winding transformer and deliver 10,000 kva from the H to the X line regardless of the load on the Y winding, provided there were not too much difference in the power factors of the two loads. This example indicates the impossibility of securing equal current division for all conditions of loading when a two-winding and a three-winding transformer are paralleled.

Example—

PARALLEL OPERATION OF 3-WINDING WITH EXISTING 2-WINDING TRANSFORMER

Given: A 5000 kva, two-winding transformer with six percent impedance transforming power from lines H to X.

Required: The impedances of a three-winding transformer to operate in parallel and supply from the H line a total load of 10,000 kva on the X line and 5000 kva on the Y line.

H winding 10,000 kva
X winding 5,000 kva
Y winding 5,000 kva

Method: If the impedance Z_H in Fig. 3 is made equal to zero and the impedance of Z_X is made equal to six percent on a 5000 kva base, it is evident that this transformer will operate successfully in parallel with the two-winding transformer for all loads. The value given to Z_Y does not affect parallel operation of these transformers.

If Z_Y is made equal to six percent, the transformer impedances become:

$Z_1=Z_H+Z_X=6\%$

$Z_2=Z_H+Z_Y=6\%$

$Z_3=Z_X+Z_Y=12\%$

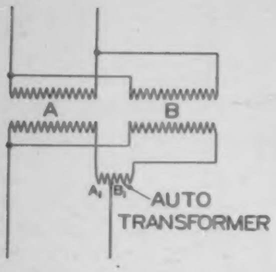


Fig. 6—Use of Auto-Transformer for Paralleling.

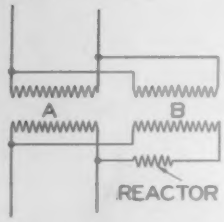


Fig. 7—Use of Reactor for Paralleling.

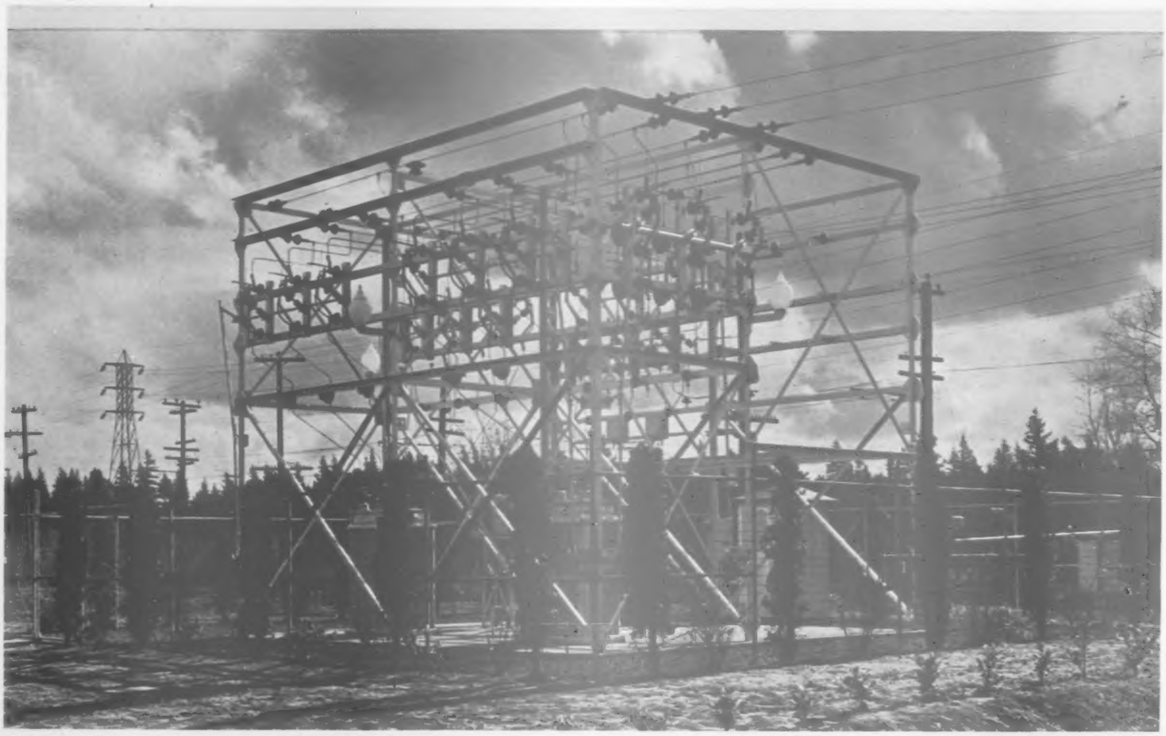
If it is desired to use this transformer to supply power from the X line to the H and Y lines, a total of 10,000 kva can be supplied safely for any combination of loads on the H and Y windings provided the kva taken by the Y winding does not exceed 5000 kva. The H winding will be underloaded, but the X winding of the three-winding transformer will carry the same load as the two-winding transformer for all conditions.

These examples show the factors involved and the methods of obtaining satisfactory parallel operation of three-winding transformers with two-winding transformers. Since each case is special, a detailed analysis of each individual case is required.

Use of auxiliary coils to secure parallel operation

When the circulating currents at no-load exceed permissible values, they may be reduced to permissible values by the use of auto transformers, sometimes called balance coils, connected as shown in Fig. 6. When the load current division is not within satisfactory limits, it may be corrected either by the use of series reactors shown in Fig. 7 or by auto transformers shown in Fig. 6.

Reactors are generally used in such cases because the necessary connections are simpler than with auto transformers. The reactor is placed in series with the transformer having the lowest impedance and should be so constructed that the percent impedance of this transformer plus the percent impedance of the reactor on the same base is equal to the percent impedance of the other transformer on its kva rating. The turns in each part of the auto transformer must be inversely proportional to the kva ratings. For example in Fig. 6, the ratio of turns in a_1 to turns in $b_1 = \frac{\text{kva of B}}{\text{kva of A}}$. The voltage of the auto transformer will be equal to the difference in voltage between the two transformers (including the difference in impedance voltage at full load and at no-load the difference in no-load voltages only).



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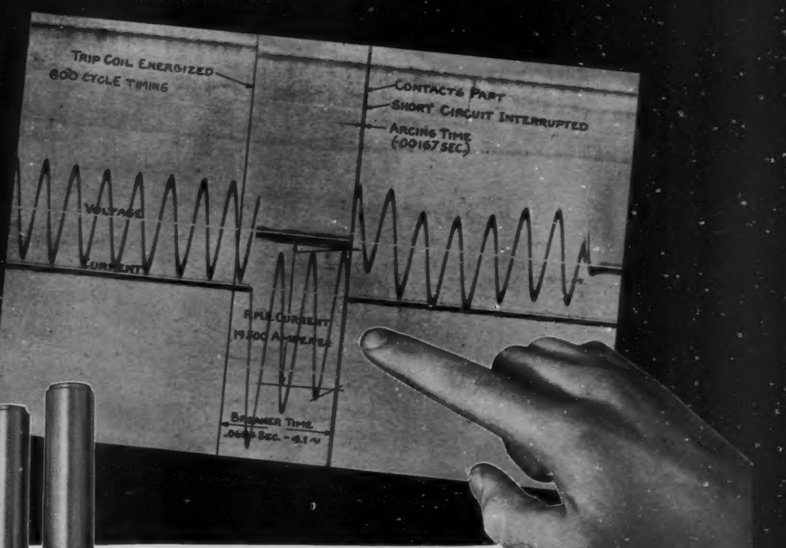

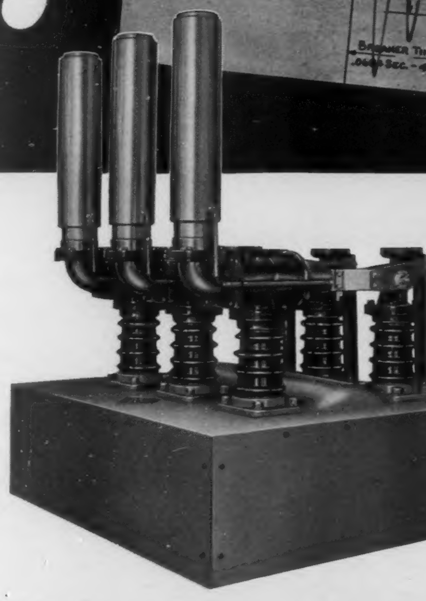

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